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FLASH RADIOGRAPHIC MEASUREMENT OF THE SHOCK COMPRESSIBILITY OF MAGNESIUM ALLOY, LUCITE, AND POLYETHYLENE

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ABSTRACT

Compressibilities of magnesium alloy, Lucite, and polyethylene, were measured during explosively induced shock, using a flash X-ray technique.

Measurements on magnesium alloy confirm earlier results from a similar experiment using small explosive charges, but show a distinctly lower compressibility than reported by other authors using free surface measurements. To a lesser extent the Lucite data show the same discrepancy. Polyethylene turns out to be less compressible than Lucite under intense shock loads.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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1. INTRODUCTION.

Materials under strong dynamic load have been extensively studied during the last decade, their behavior under extreme conditions being of high interest in solid and liquid state physics. Likewise, strong shock phenomena play an important part in many ballistic events, such as in hyper-velocity impact, which is of high interest now in space research.

An important quantity for the description of the physical behavior under dynamic conditions is the shock compressibility. When the compression rate ρ/ρ_o behind a plane shock front and the velocity V of shock wave propagation are known, pressure p can be deduced from the relation

$$p = \rho_o V^2 (1 - \frac{\rho_o}{\rho}) \tag{1}$$

which follows immediately from mass and momentum conservation. The pressure-density relationship for plane shocks is generally known as the Hugoniot curve which is commonly plotted in terms of pressure versus relative specific volume. Experimental determination of shock speed V is no particular problem, whereas measurement of densities in extremely short times is much more difficult. Basically there are three different experimental procedures today to obtain experimental points on the Hugoniot curve:

a. The X-ray flash method.[1*]

Following this technique one determines the density behind the shock front from the absorption the compressed area offers to X-rays. Absorption measurement is done by densitometric evaluation of flash radiographs. The method needs X-ray flashes which are so short that local pressures do not vary substantially during the exposure time ($\sim 10^{-7}$ sec).

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* See literature cited

b. **The free-surface method.** [2]

This method is purely kinetic. Density ratio is deduced from the speed U of material flow behind the shock front and the shock speed V using the relation

$$\frac{\rho}{\rho_o} = \frac{V}{V-U} \tag{2}$$

which reflects mass conservation in the stationary wave. Since no precise method for a direct determination of U is known, U is calculated from the velocity U_f , to which particles at a free surface normal to the shock path are accelerated when the shock reaches this surface. Assuming that during pressure release thermal equilibrium is always established, one can show that U_f is fairly close to 2 U.

c. **The collision method.** [3]

The shock is produced by plane collision of a flat projectile impinging on a plane target. Pressure and density in the target can be calculated from the impact velocity of the projectile and the shock speed in the target, provided that either the projectile and the target are of the same material, or the Hugoniot of the projectile material is known. This method requires very rapid projectiles, the firing of which is expensive and the planarity of which is difficult to maintain.

Experimental results following these three procedures have been reported for many materials. [4,5,6] Data obtained with the different methods agree roughly; they show, however, some discrepancies in detail. For instance, radiographic measurements systematically give somewhat lower compressibilities than free surface results. [7] For a given pressure, differences in corresponding density often exceed 2% of the initial density and are therefore beyond the experimental error of either method.

Tests described in this report have been conducted in the course of a research program, the objectives of which were, first, to shed some light on the origin of this disagreement, and second, to extend the pressure range

covered today by radioflash measurement to values above 0.2 mb.

For technical reasons which will be elucidated later on, the tests were concerned only with materials having a rather feeble X-ray absorption power such as light metals and plastics.

Russian authors recently have reported experiments where especially high shock pressures were obtained by reflection and crossing of shock waves.[8] Though these shocks were also recorded by flash radiography, pressure-density relations were determined only from geometrical shock configuration and not from absorption measurement. Maximum pressures reported in this paper range up to 900 kb. Since these pressures are obtained by two-stage impulse, compressibilities are not directly comparable to one-stage shock results and will not be referred to here.

2. EXPERIMENTAL TECHNIQUE.

Strong shocks can be generated either by direct attack of detonating high explosives or by ballistic impact. High explosives may also be used to propel the projectiles rapidly enough for high impact pressures. An often-applied technique is to launch an explosive-driven metal plate which after a short distance hits the specimen to be investigated. In this way substantially higher pressures can be obtained than by direct explosive attack.

While in the free surface method the amount of high explosive to be fired in one experiment is not essentially limited, the radioflash technique allows only the application of rather small charges, since the film has to be quite close to the specimen and the film must be protected from the blast. For technical reasons, explosive charges of only 10 - 30 gr have been used for radiographic measurement until now. Although detonation shock pressure should not depend on explosive size (provided that all dimensions are large compared to the reaction zone length [0.1 - 0.5 mm]), border effects play, of course, a more important part, and pressure duration is shorter for smaller charges. It seemed therefore worthwhile to operate with higher amounts of explosive in order to investigate whether the explosive size influences the compressibility measurement.

Bigger charges need stronger film protection and hence a more penetrating radiation than has been used until now. A portable 500 kv flash device is being developed for this purpose. Pending the development of this device, a smaller 200 kv apparatus was used up to its limits. Since this apparatus allowed the explosive quantity to be increased only slightly, different ways were found to reduce border effects: by means of a heavy confinement, effects of bigger charges were simulated; or by a convenient charge shape, border effects were drastically reduced.

Figure 1 shows the experimental device for shock generation with a confined explosive. Both the cylindrical specimen and the explosive charge are contained in a borehole of a heavy steel block. In this block two radial slits are milled for the radiographic observation. The specimen increases its diameter step by step, corresponding to diameter increments of 10, 20, or 30% for magnesium, and 20 - 80% for the plastics under study.

This specimen configuration allows the calibration of film blackening. The measurement is based on the fact that absorption is an atomic effect, so that higher density is equivalent to a correspondingly bigger absorber thickness. This becomes evident from the absorption law

$$I(X) = I_o e^{-\frac{\mu}{\rho} \cdot \rho \cdot x}$$

where

x = absorption thickness

ρ = density

$\frac{\mu}{\rho}$ = mass absorption coefficient

I_o = initial intensity

$I(X)$ = outcoming intensity

Taking the data measurement (the film density when viewed through the shock wave) and the calibration measurement on the same film eliminates all errors due to film sensitivity, processing, etc.

A primacord ignited with the same detonator which initiates the main charge serves as a high-speed clock; it is radiographed with the phenomenon (figure 1), and the position of the detonation front indicates the time point of the radioflash.

The primacord is further used to trigger the flash: by the ionization of the detonation products the resistance between two wires fixed on the cord breaks down. This fires a first thyratron in an electronic delay system. After a controllable delay a second thyratron is fired; this furnishes the high voltage impulse to trigger the radioflash tube.

Generally 210 kv was applied to the tube anode. This voltage gives a spectral distribution of the emitted radiation for which the specimen thickness for magnesium and common plastics is roughly equal to the thickness of half absorption. Contrast conditions are optimized in this way.

Figure 2 gives a schematic drawing of the total setup used for radioflash records. The radiographic equipment is protected by a 60-mm armour plate. This plate has an aperture covered by a 4-mm magnesium alloy metal plate through which the X-ray source is viewed. Film is contained in a casing with a front plate of 10-mm steel, in which slits have been cut at the areas of interest, i.e., the shock phenomenon and the primacord clock. These slits are covered by 8-mm magnesium alloy.

This protection was effective against the blast, but was sometimes penetrated by small fragments spalled either from the specimen or from the confining material. Particle impact on the intensifier foils and the film gave disturbing impressions on the film. As indicated in figure 2, the steel block was therefore oriented in such a way that spalled fragments hit the protective front plate of the film container.

Flash tubes applied for these tests were sealed-off pyrex glass tubes with tungsten anode (type ISL/RX 615).

In the experimental setup of figure 1 different kinds of high explosives have been used to generate shock pressures:

    a. Pressed PETN with 5% wax

  b. Cast RDX/TNT 65/35

  c. Cast baratol (TNT/RDX/bariumnitrate 30/10/60)

Cast charges were detonated with a PETN booster. Explosive weights of 50-60 gr were used in this series of experiments.

Figure 3 shows a typical radiograph of a detonation shock in plexiglas, 0.5 μ sec after the detonation front has reached the specimen border. The experimental arrangement used requires a very high precision in trigger timing, since the shock has to be caught by the radioflash within a path of only 10 mm. Triggering of the flash shows only a scatter of 0.2 μ sec, so that the required precision can easily be obtained.

Figure 4 gives a densitometric curve obtained from a radiograph like figure 3. It shows the photometer response recorded from the different calibration steps, the original material, and the shocked material. The record allows correlation of the absorption jump in the shock front with the density variation. At the shock front the densitometer curve presents a slope quite similar to that at the calibration steps. This means that the indicated shock width is merely due to geometrical and focus size effects and not to motion blur. A particular local density can be measured with an error of $\pm$ 1.5%. This allows mean values to be determined with an accuracy of $\pm$ 1% of the initial density ρ_o.

The small variation of shock path for radiographs of the type shown in figure 2 has the disadvantage that the shock speed can only be determined with a precision of the order of $\pm$ 5%, the primacord clock having an error of $\pm$ 0.05 μ sec. Wave speed had therefore to be measured in particular tests using longer shock paths. In these experiments, two 40-mc counters were used as more precise time recorders in combination with foil probes. The electric circuit used for these measurements is shown in figure 5. Travel times for the shock over two different paths were indicated. This made it possible to determine wave attenuation and to eliminate probe influences. Counters were fully transistorized and manufactured in this laboratory.

Sometimes in the course of these velocity measurements, results seemed to be influenced by the presence of the steel confinement: the indicated speeds were obviously higher than reasonably could be expected. This probably was

due to a jetting effect in small gaps between specimen and confinement.

This higher speed and the above-mentioned difficulties in film protection led us to search for an unconfined charge design giving no essential border effect. The solution found for this problem is represented in figure 6. The shape of a truncated cone was given to the explosive charge which was initiated at the base by a plane wave generator. The specimen was located at the smaller face. The cone angle (76°) was chosen in such a way that the release wave starting at the free surface could not disturb the planarity of the detonation wave. A total explosive weight of 175 gr was used for this kind of shock generator.

Figures 7 and 8 represent flash radiographs obtained with this technique showing detonation shocks in Lucite and polyethylene. A slight tilt of the shock front, which can be recognized on the radiographs, has its origin doubtless in release waves centered at the specimen surface. This is, however, no handicap for the densitometric evaluation provided that density drop behind the shock front is not too steep.

Only Comp. B has been used until now as driving explosive in the arrangement of figure 6. Shock velocities could roughly be estimated from time measurements with two primacords attached to the charge; more precise measurements were again obtained with the counter technique.

3. RESULTS.

Experimental results obtained following the experimental procedures described in the foregoing section are compiled in table 1. Indicated $\frac{\rho}{\rho_o} = \frac{v_o}{v}$ data are mostly mean values from several measurements. Velocity V is always corrected to the real photographed shock position.

Results are plotted as p-v curves for the three investigated materials (figures 9 - 11). These plots allow comparison of the present results with earlier ones and with those of other authors.

Most of the experiments concern polymethylmetacrylate, commonly known as plexiglas, perspex, or Lucite. The present results (figure 9) have been obtained with a Lucite product of Alsthom (France). They are plotted as

Table 1

Explosive	Setup	V (mm/μsec)	ρ/ρ_o	v/v_o	p (kb)
Lucite ρ_o = 1.18					
Comp B	unconfined	6.265	1.51	0.662	159
Comp B	confined	5.800	1.46	0.685	127
PETN	confined	5.330	1.42	0.705	102
baratol	confined	5.140	1.39	0.72	89
Dow Metal (96% Mg, 3% Al, 1% Zn) ρ_o = 1.79					
Comp B	unconfined	7.235	1.23	0.813	178
Comp B	confined	7.180	1.22	0.820	170
PETN	confined	6.250	1.19	0.836	117
Polyethylene ρ_o = 0.93					
Comp B	unconfined	6.350	1.48	0.676	124
PETN	confined	6.020	1.36	0.735	91

open circles, the corresponding p-v curve as a broken line.

First published data on Lucite, obtained from free surface measurement, have been reported by BUCHANAN et al.[9] They show substantially higher compressibility (figure 9). There are, however, earlier (and probably more precise) free surface experiments on Lucite conducted by the Los Alamos group*. Their data are plotted as full circles. Moreover, another point,

* Private communication by J.M. WALSH and F.L. YARGER, 1955.

determined by BAKANOV and TRUNIN, has been reported by AL'TSHULER[8]. These values are fairly close to the present X-ray results, the difference in density indicated for a given pressure being less than 2%.

DAPOIGNY, KIEFFER, and VODAR[10] determined p-v values from angular relations observed on flash radiographs showing lateral detonation shocks in plexiglas. Their values (figure 9) exhibit again a much higher compressibility than the present data.

It is of particular interest to compare the recent results on magnesium alloy with those reported from earlier experiments with much smaller charges[7] (figure 10). The present data (open circles) lie indeed very well on the earlier curve (plotted again as a broken line). It seems, therefore, that charge size does not affect the measurement to a remarkable extent. The discrepancy found for this particular material between radioflash data and free surface results (full points) obtained on practically the same magnesium alloy by the Los Alamos group* does still fully persist. The X-ray curve parallels well BRIDGMAN's static measurements in the 50 - 100 kb range with a shift explained by the fact that pure magnesium was studied statically. The dynamically measured Hugoniot for pure magnesium[11] exhibits an analogous shift with respect to the alloy curve.

Figure 11 shows the Hugoniot for polyethylene as it comes out from the present experiments. It is worthwhile to note that polyethylene, though softer and more easily compressed under slight static pressure, turns out to be less compressible under intense shock load than Lucite. No comparable results seem to have been published until now on this material, which is frequently used for model tests in hypervelocity impact research.

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*Private communication by J. M. WALSH and F. L. YARGER, 1955.

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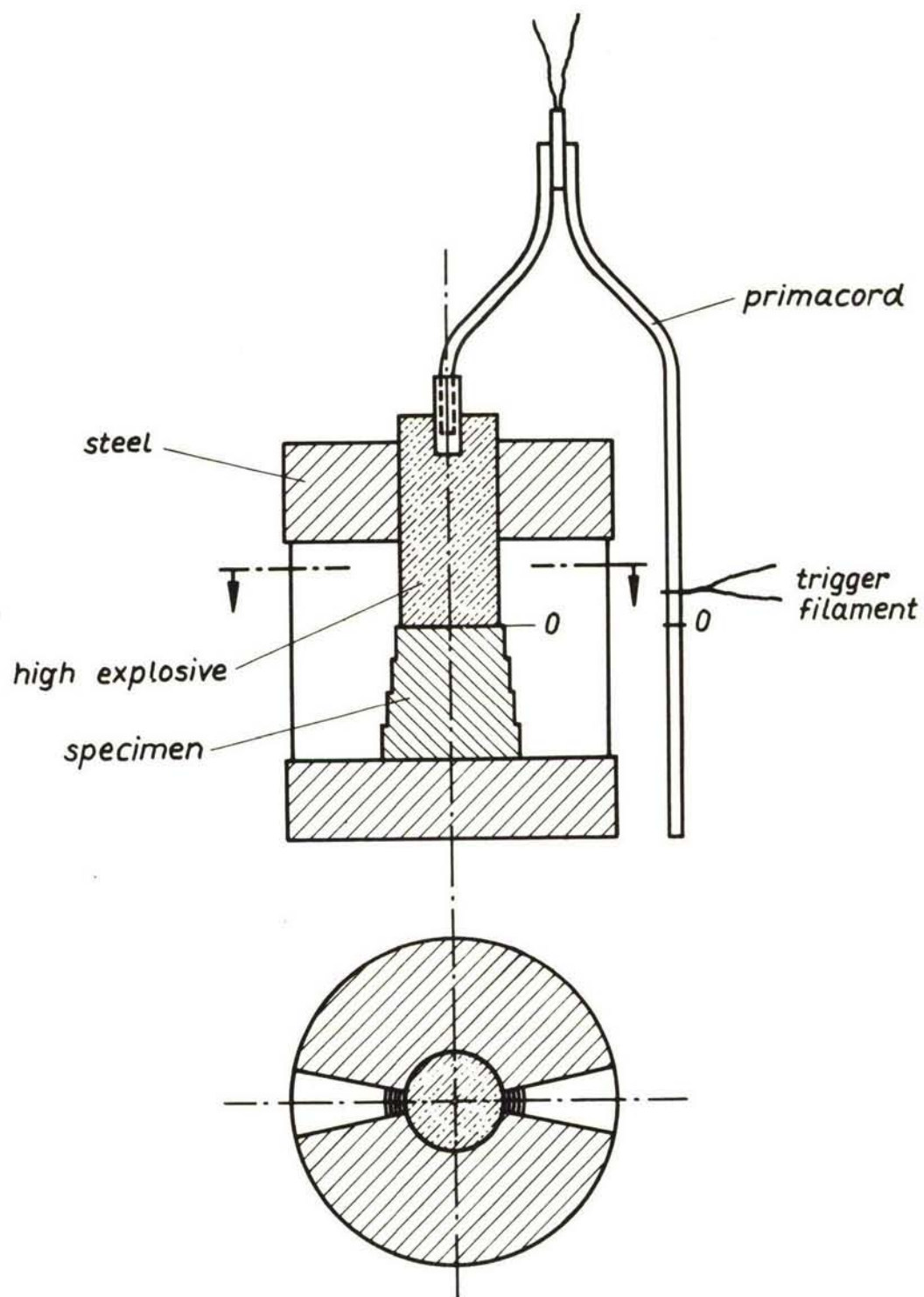11. WALSH, J. M., RICE, M. H. McQUEEN, R. G., and YARGER, F. L. Phys. Rev. 108, 196. 1957
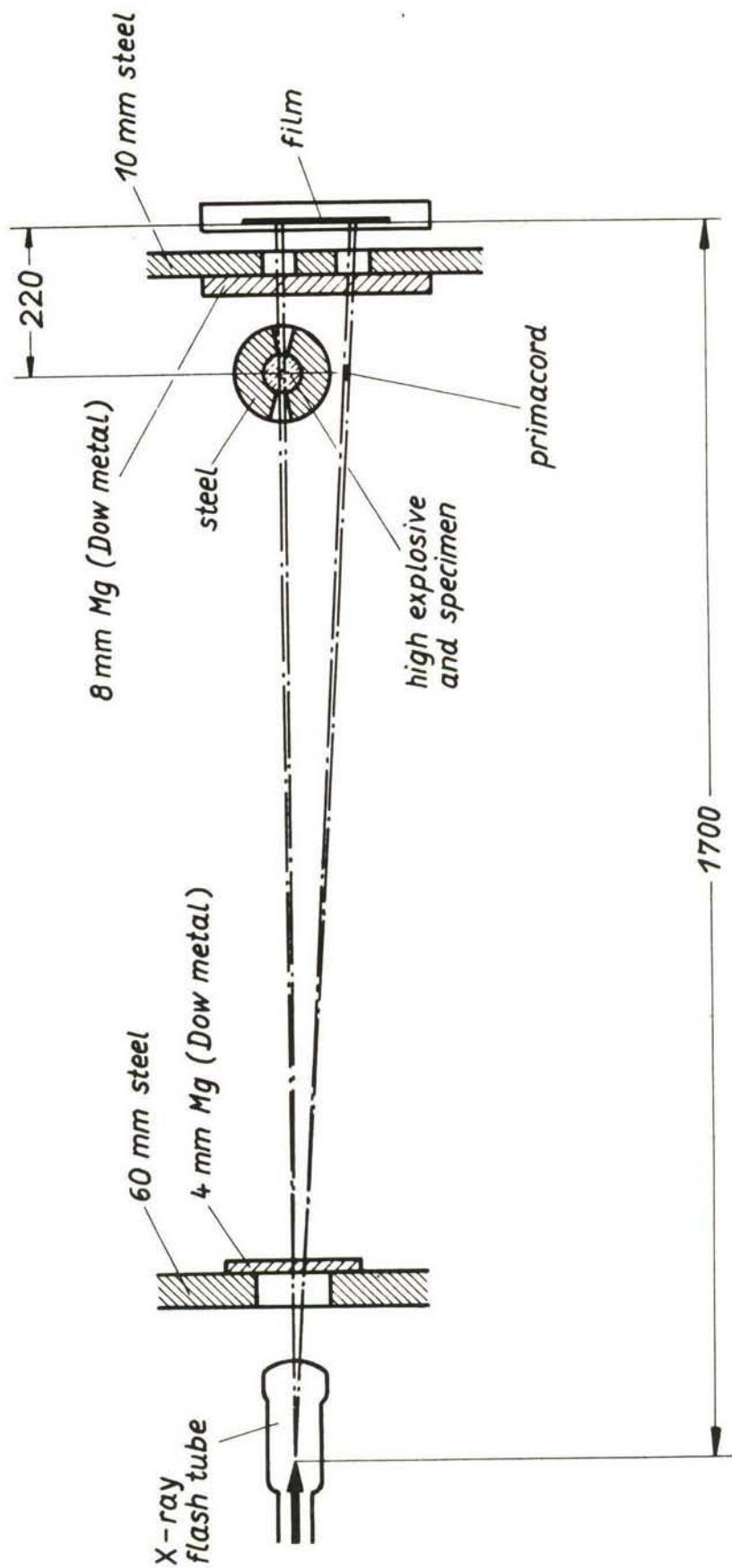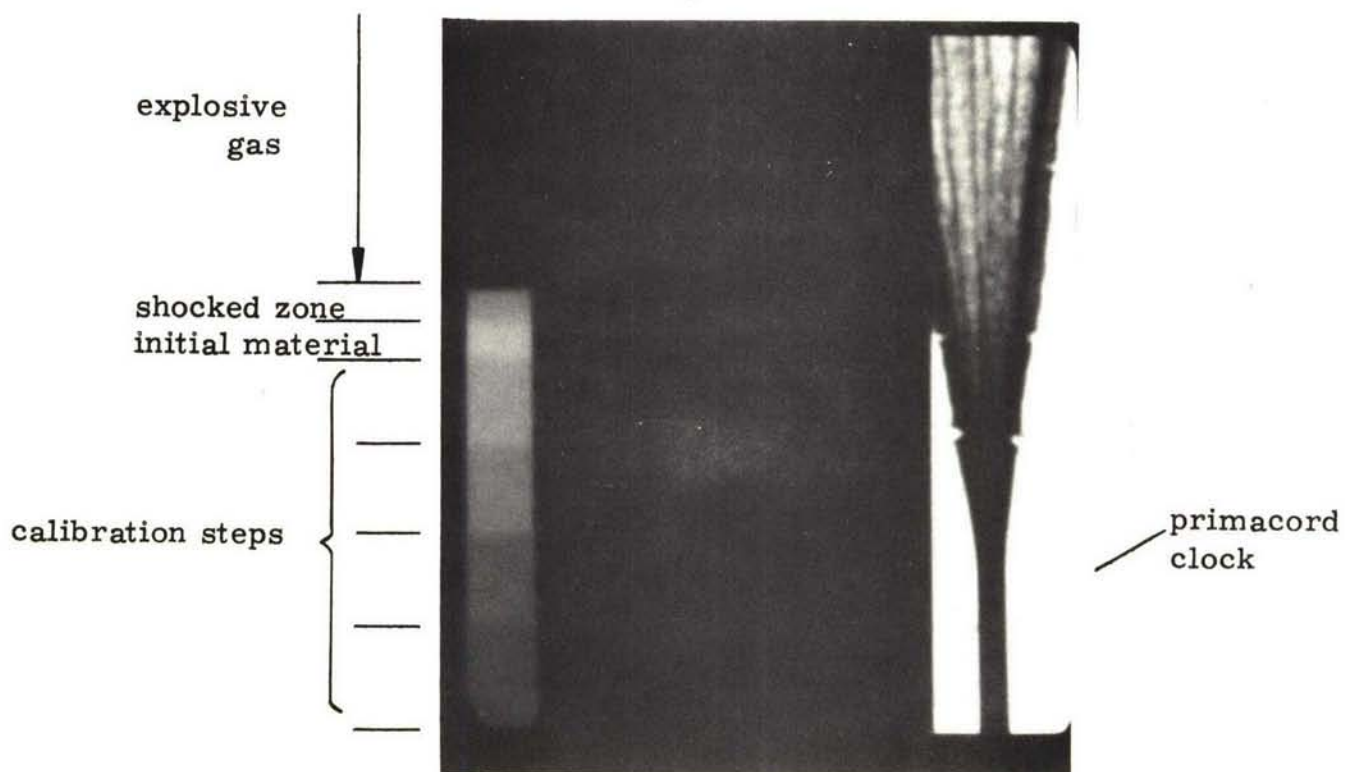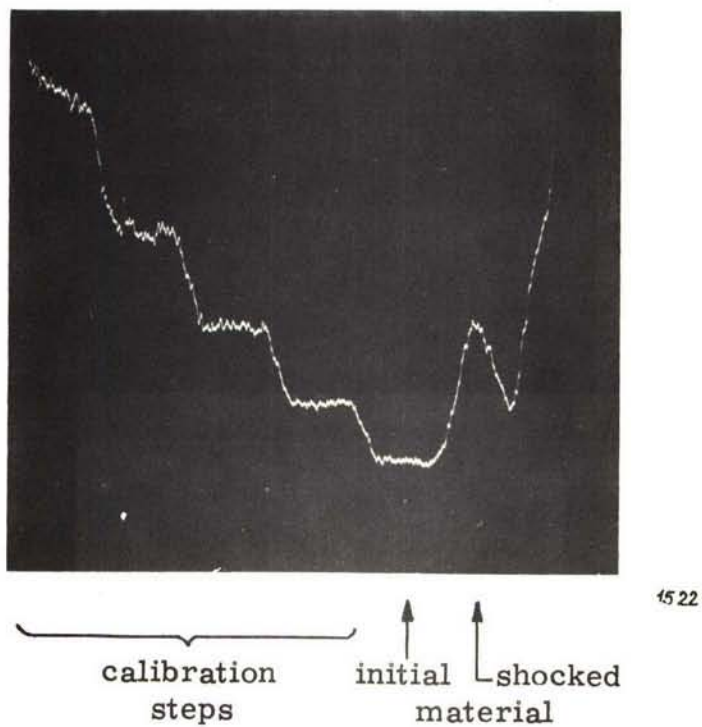
Figure 1. Experimental setup.

Figure 2. Experimental device for flash radiography.

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Figure 3. Flash radiograph obtained with
the device shown in figure 2.

Figure 4. Densitometer record of a flash
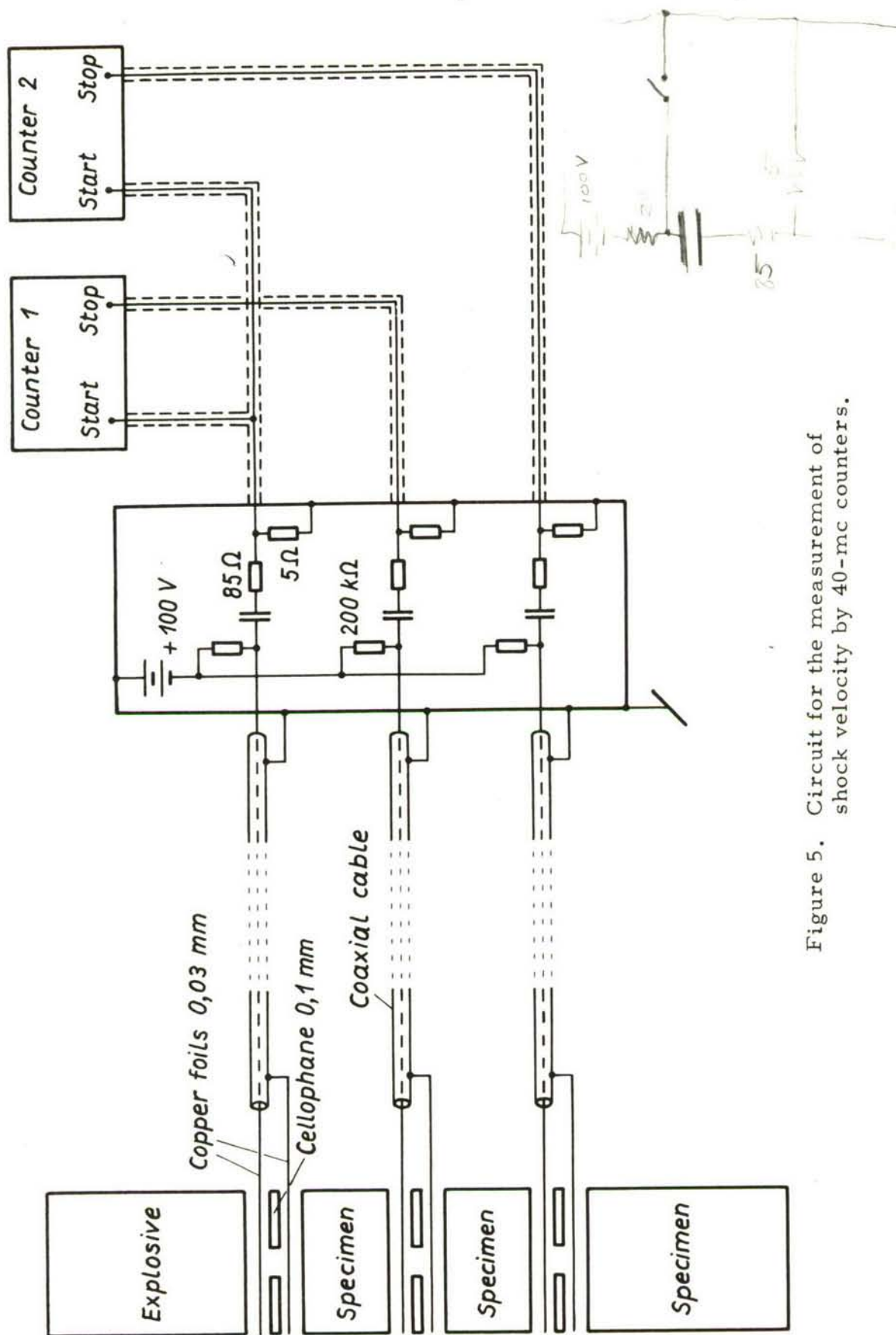radiograph according to figure 3.

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Figure 5. Circuit for the measurement of shock velocity by 40-mc counters.
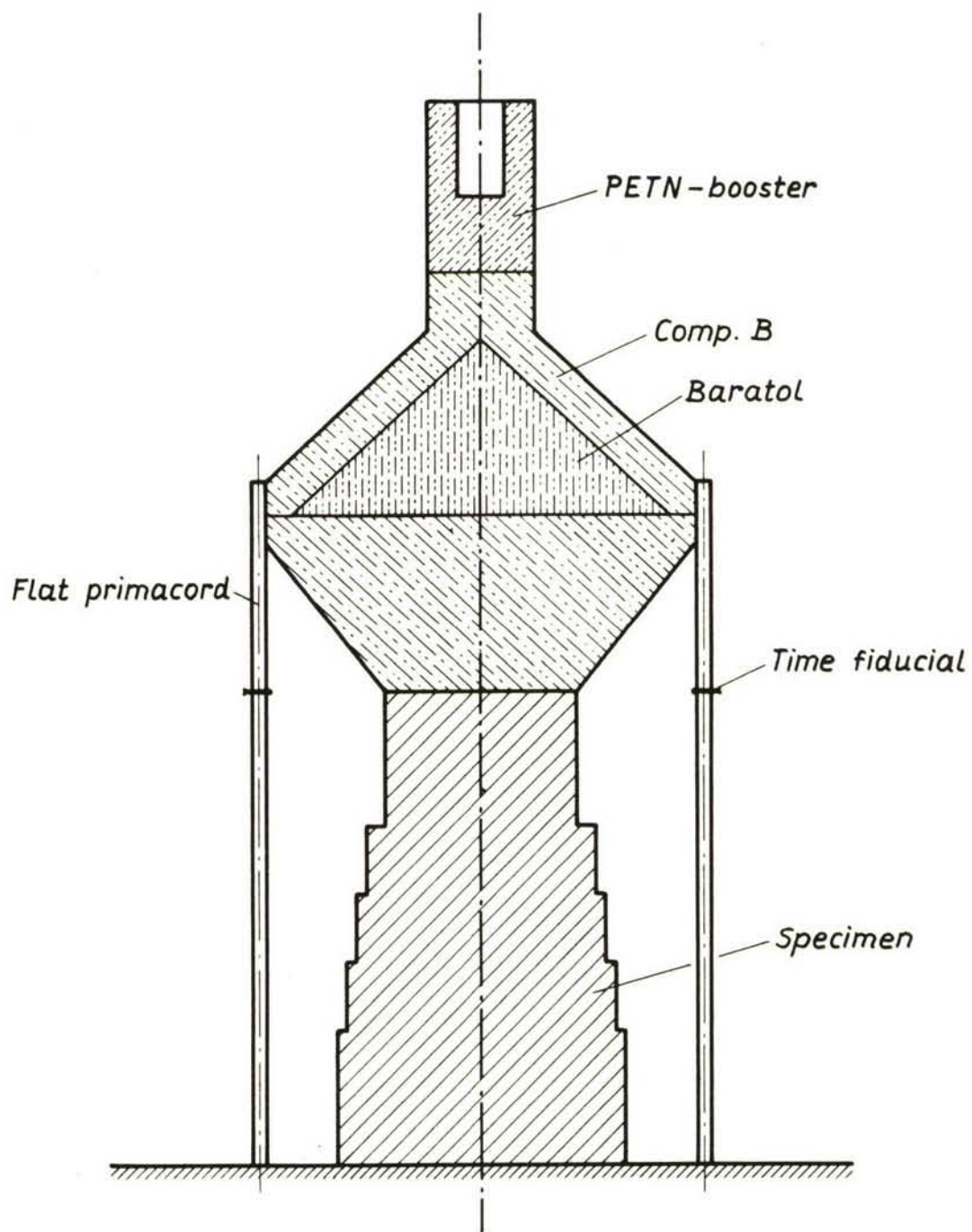
Figure 6. Unconfined charge without border effect.
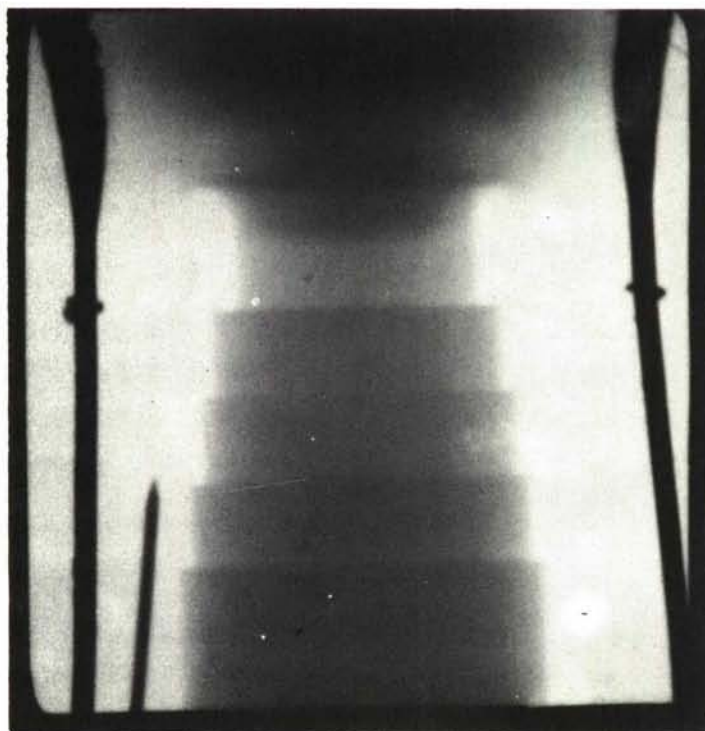
Figure 7. Flash radiograph of a detonation shock in
Lucite. (Experimental setup - see figure 6.)

Figure 8. Flash radiograph of a shocked polyethylene specimen.

*Plexiglas
(Perspex)*

Figure 9. Experimental p-v curves for polymethylmetacrylate (plexiglas, perspex, Lucite) obtained from different methods.

Figure 10. Shock Hugoniots for Dow Metal (96% Mg, 3% Al, 1% Zn) from surface and radioflash measurement and static p-v curve for magnesium.

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Figure 11. p-v curve for polyethylene (X-ray flash technique).

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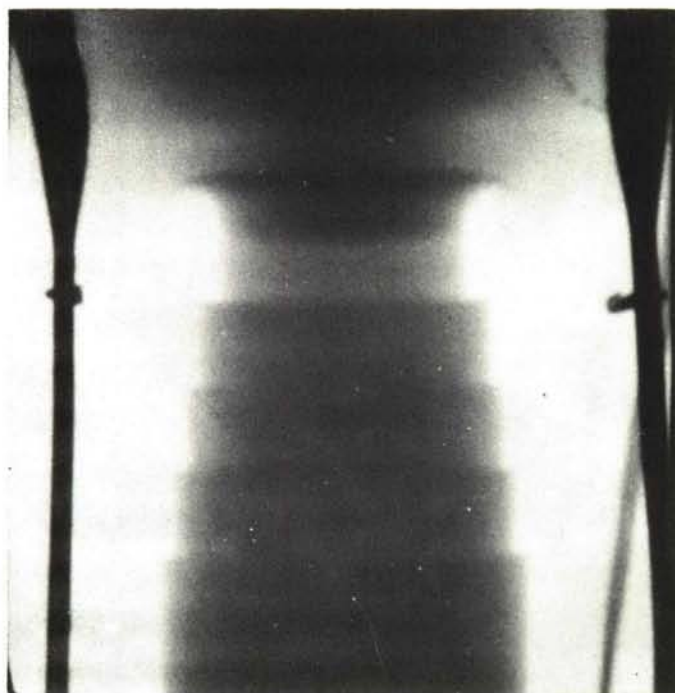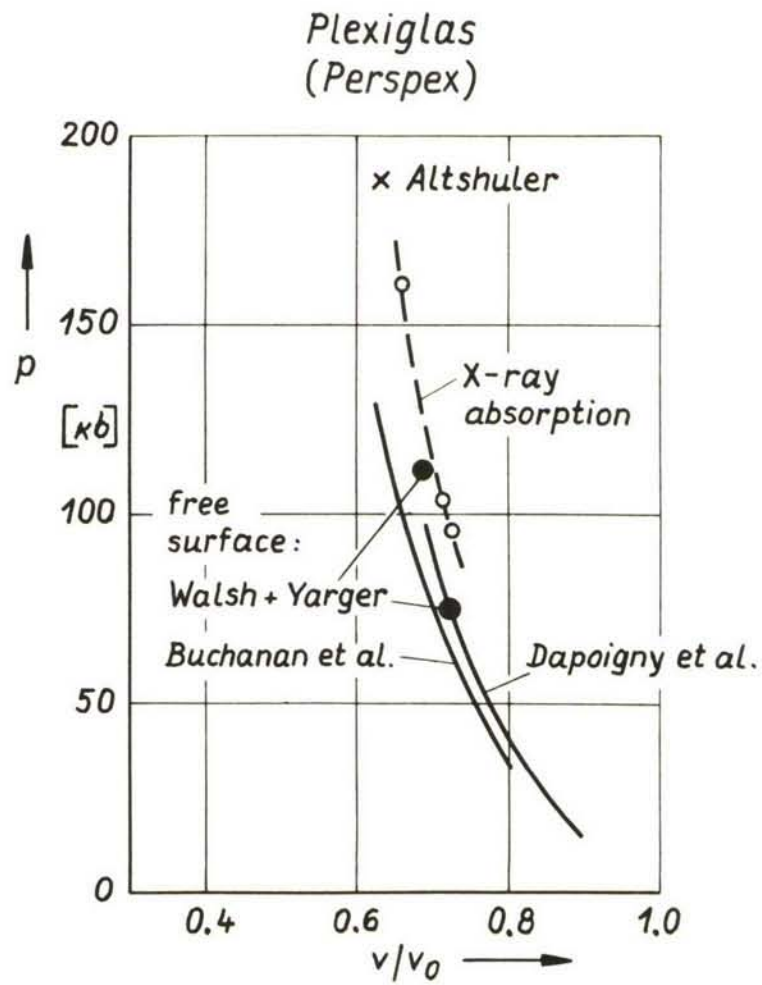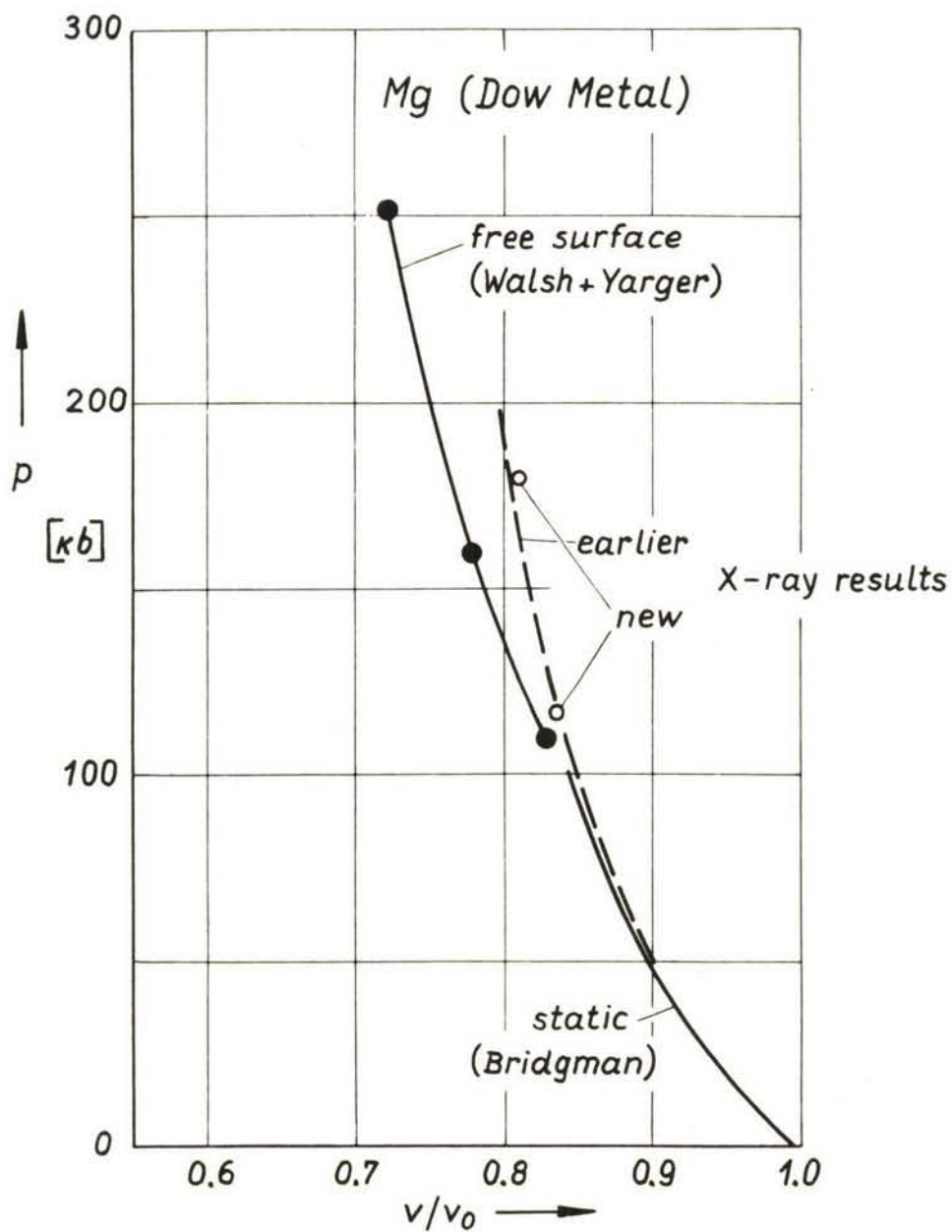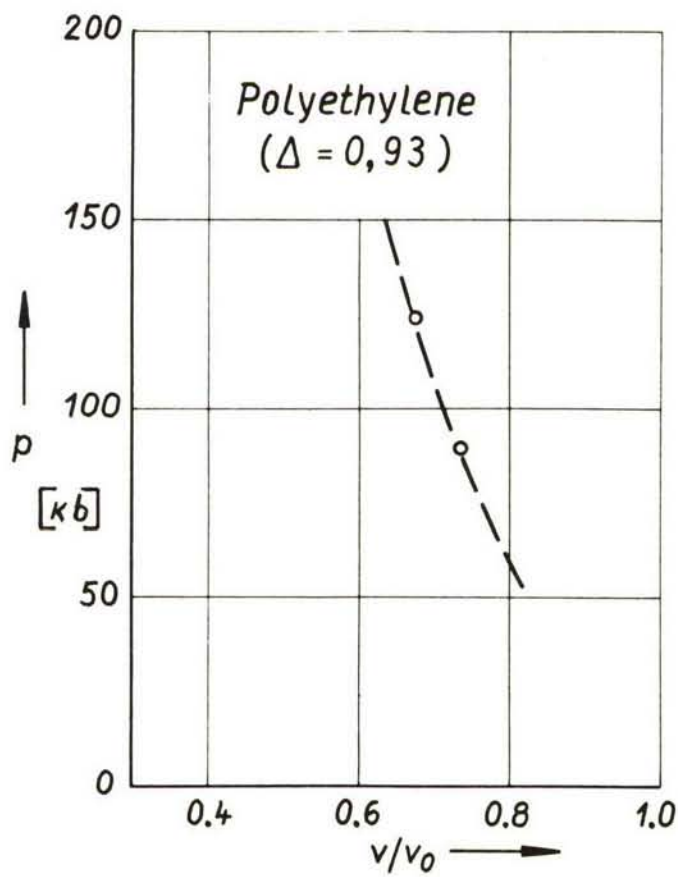|	
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MEASUREMENT OF THE SHOCK COMPRESSIBILITY OF
MAGNESIUM ALLOY, LUCITE, AND POLYETHYLENE
28 p. incl illus., tables, 11 refs. October 1962

Unclassified report

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1. Absorption
2. Impact testing
3. Plastics -- effects of blast
4. Pressure testing
5. Shock waves
6. Structural materials -- effects of blast
7. X-radiation
I. AFSC Project 5776, Task 577601
II. Contract AF EOAR Grant 61-52
III. German-French Research Inst., Saint-Louis, France
IV. R. Schall, G. Thomer
V. In ASTIA collection

Air Force Special Weapons Center, Kirtland AF
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